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## Use of GIS-Based Site-Specific Nitrogen Management for Improving Energy Efficiency

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# Use of GIS-Based Site-Specific Nitrogen Management for Improving Energy Efficiency

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# 21 Use of GIS-Based Site-Specific Nitrogen Management for Improving Energy Efficiency

*Kevin F. Bronson, Peter C. Scharf,  
and Newell R. Kitchen*

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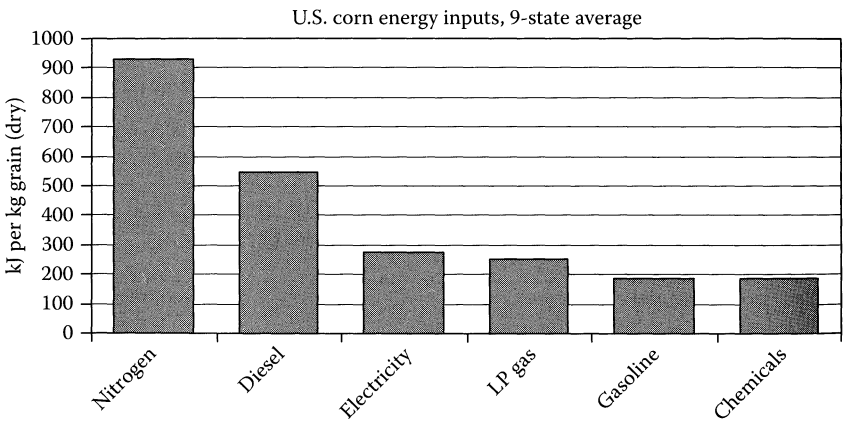
# 21.1 EXECUTIVE SUMMARY

To our knowledge, geographical information system (GIS)-based site-specific nitrogen management (SSNM) techniques have not been used to assess agricultural energy costs and efficiency. This chapter uses SSNM case studies for corn (*Zea mays* L.) grown in Missouri and cotton (*Gossypium hirsutum* L.) grown in Texas. In five case studies, the impact of SSNM will be compared with blanket N fertilizer recommendations. The five case studies are investigating (1) the impact N on energy produced in cotton production, (2) the impact of variable-rate N for cotton production based on soil nitrate and crop reflectance, (3) the feasibility of variable-rate N based on corn crop reflectance, (4) the use of corn management zones and crop reflectance for improving N recommendations and energy efficiency, and (5) the ability of using aerial photographs to improve N recommendations in corn.

# 21.2 BACKGROUND

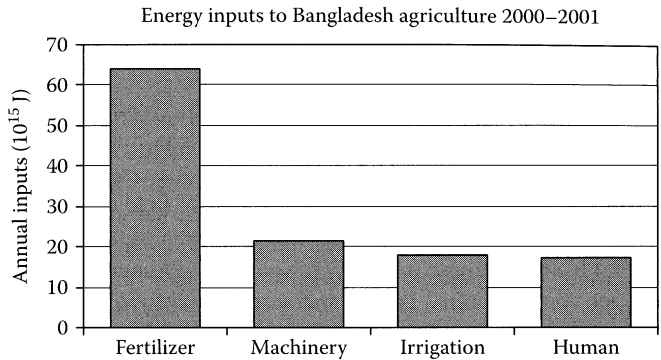
In production agriculture, nitrogen (N) is a nutrient that often limits crop growth and when applied at rates that are sufficient to optimize yield, represents one of the single largest energy investments. Nitrogen fertilizer use, which has increased 80 times since the 1920s has contributed to worldwide yield increases.<sup>1-3</sup> In the United States, corn, wheat, and cotton use 70% of total fertilizer used, with corn accounting for 50% of the N.<sup>4</sup> Asia is one of the areas in the world where it is used, and resulting yields are expanding rapidly. Higher yields are needed to feed an expanding population that desires more meat in their diets.

One of the primary energy costs of cropping systems is associated with N fertilizer.<sup>5</sup> Most commercially available N fertilizer is made from nitrogen gas (N<sub>2</sub>) which makes up 70% of the atmosphere. To convert the N<sub>2</sub> molecule to a biological active form requires a large amount of energy (Figures 21.1 and 21.2). Not all N sources have the same energy production requirements (Table 21.1). Of the commonly used



**FIGURE 21.1** Nitrogen fertilizer is the dominant energy input for corn (maize) cropping systems in the United States. (Data from Shapouri, H. et al., The energy balance of corn ethanol: An update/USDA Agricultural Economic Report No. 813, 2002.)





**FIGURE 21.2** Fertilizer is the dominant energy input for cropping systems (mainly rice) in Bangladesh. (Data from Alam, M.S. et al., *Am. J. Environ. Sci.*, 1, 213, 2005.) Breakdown of fertilizer energy into NPK is not given, but is dominantly for N.

**TABLE 21.1**  
**Energy Needed for the Production of Common N Fertilizers**

N Fertilizer Source	N Concentration (%)	Energy Production Requirement ( $\text{MJ kg}^{-1}$ N)
Ammonia	82	55
Ammonium sulfate	21	58
Liquid UAN	32	65
Ammonium nitrate	34	67
Urea	46	70

*Source:* Adapted from Hood, C.F. and Kidder, G., Fertilizers and energy, Fact Sheet EES-58, November 1992, Florida Cooperative Extension Service, University of Florida, 1992.

N fertilizers, anhydrous ammonia has the lowest amount of energy associated with its production and transport. Most of the energy cost is in the production of N fertilizer, and only a small proportion of energy is expended for transport and application.<sup>6</sup> Kuesters and Lammel<sup>7</sup> reported that the energy requirement for transporting a kilogram of urea 8000km by sea was  $5.56 \text{ MJ kg}^{-1}$  urea-N, while the energy requirement for producing the urea was 8400MJ. Natural gas is the main energy input into the production of N fertilizer.<sup>3</sup>

Although N fertilizer has increased crop yields, the overapplication of N can have unintended negative economic and environmental consequences. Both environmental and efficiency-related concerns have fueled thousands of field studies of N fertilizer management, cycling, export, and balances in various cropping systems. Nitrogen behavior in soil turns out to be remarkably complex. The fates of N fertilizer not utilized by plants include  $\text{NO}_3^-$  leaching, ammonia volatilization,

immobilization into soil organic matter, fixation in clay particles, and denitrification. Nitrous oxide is a product of denitrification and nitrification and is a potent greenhouse gas. Emissions of  $\text{N}_2\text{O}$  increase several fold in soils following N fertilization.<sup>8–10</sup> Management strategies to reduce N loss and increase crop N recovery have been studied extensively, including N fertilizer source, application method, timing of fertilizer application, tillage, N loss inhibitors (fertilizer additives), and, more recently, site-specific management to account for within-field crop N needs.<sup>11,12</sup>

Nitrogen use efficiency (NUE) in terms of its recovery by row crops is generally less than 50%.<sup>13,14</sup> In spite of these relatively low values, agronomic NUE (i.e., increase in grain yield per unit of applied N) has increased in corn 36% since 1980.<sup>14</sup> Much of this improvement is due to cultivar development, but higher plant populations and improved soil management practices, such as conservation tillage, contribute as well. Improved N management practices include less fall-applied N fertilizer and more split N applications.<sup>14</sup> Plant breeding has clearly made major contributions to corn and wheat yield gains the last several decades. Studies in wheat<sup>15</sup> and corn<sup>16</sup> have compared historical cultivars with modern ones and found an increase in agronomic NUE. With wheat, agronomic NUE was reported to have increased between 1950 and 1985 by 1% year<sup>-1</sup>, evenly divided between gains in N recovery and physiological NUE.<sup>15</sup>

Reducing trade deficits and improving energy independence are also rationale for improving NUE in agriculture. Using the United States as an example, most (52% in 2007) of N fertilizer used is imported,<sup>17</sup> whereas in 1992, only 25% of N fertilizer was imported.<sup>4</sup> This reflects a trend seen over the last 15 years of decreasing U.S. N fertilizer production, and an increased reliance on imported N fertilizer from Russia, Ukraine, Egypt, and Trinidad. This change is the result of higher natural gas costs in many developed nations.

Nitrogen best management practices include  $\text{NO}_3^-$ -N soil testing, considering all sources that provide N to the crop, proper timing of application, sound water management and fertigation, proper calibration/operation of equipment, and realistic yield goals.<sup>3,18–20</sup> Over the past 15 years, these practices have been tested in a large number of research projects.<sup>19</sup>

Precision agriculture is an area that has only recently been explored. In precision agriculture, site-specific inputs are based on locally derived soils, soil test results, yield goals, and landscape positions. The interest in SSNM is driven by decreases in the costs of obtaining spatial information using GIS and increasing fertilizer costs. Site specific or variable-rate N fertilizer management strategies include: grid soil sampling management zone-based soil sampling, yield map/yield goal approach, and canopy reflectance-based N management.<sup>21–30</sup> Variable-rate N management can also reduce  $\text{NO}_3^-$  runoff and leaching losses and  $\text{NO}_3^-$  leaching.<sup>31–33</sup>

SSNM is one approach that might improve agricultural energy efficiency. With respect to N fertilizer inputs, SSNM can increase the net energy output if

1. N fertilizer use is reduced, without reducing yields
2. N fertilizer use is maintained or increased, but that yield responses to N are greater

Among most SSNM studies, only a few have demonstrated improved NUE by both processes. Inman et al.<sup>34</sup> classified irrigated cornfields in Colorado into low-, medium-, and high-productivity management zones, based on bare soil imagery and farmers' input. Nitrogen uptake and N fertilizer response varied by zone, suggesting that SSNM can be implemented based on management zones. Historically, yield goals have been part of U.S. corn N recommendation algorithms. However, Scharf et al.<sup>25</sup> reported that in humid environments, corn yield spatial variation is a weak predictor of economically optimum N rates (EONR). Spatial variation in the soil N supply is often more important. Plant spectral reflectance may provide the information needed to assess N supply.

Scharf and Lory<sup>28</sup> and Kitchen et al.<sup>30</sup> in Missouri, and Schmidt et al.<sup>29</sup> in Pennsylvania, estimated EONR in corn using spectral reflectance. They achieved the best predictions by using reflectance ratios of the area of interest relative to a well-fertilized area. Yabaji et al.<sup>20</sup> reported that basing in-season SSNM of drip-irrigated cotton on canopy reflectance resulted in 17–28 kg N ha<sup>-1</sup> savings in N fertilizer compared to regional N recommendations, without reducing lint and seed yields. Bronson et al.<sup>24</sup> compared variable-rate N applications based on grid soil sampling to blanket regional N management in a 3-year study of center-pivot irrigated cotton. In just 1 year out of 3 years, variable-rate N resulted in a greater lint yield response than blanket N. The average variable-rate N fertilizer application rate was nearly identical with the blanket N fertilizer rate all 3 years.

Life-cycle analysis and greenhouse gas budgets are increasingly being used to determine agricultural energy and system efficiency.<sup>35–38</sup> Tilman et al.<sup>37</sup> reported that the energy output to input ratios were marginally positive for corn ethanol, and that perennial grasses for cellulosic conversion of biomass to ethanol have a relatively high energy ratio. This ratio is very sensitive to energy inputs and generally decreases with increasing N. For example, soybean, which does not require N fertilizer, has a relatively high-energy output to input ratio. However, different recommendations can result if energy yields are the selection criteria. Kuesters and Lammel<sup>7</sup> reported that N fertilization resulted in a fivefold gain in energy in wheat and sugar beets grown in Germany. This was despite the fact that the optimal N fertilizer rates (160 kg N ha<sup>-1</sup> in wheat and 120 kg N ha<sup>-1</sup> in sugar beet) were 40% of the total energy input. Hülsbergen et al.<sup>39</sup> had similar results and reported that N fertilizer rates required to optimize energy yields were higher than the N needed to maximize the ratio for wheat, sugar beets, potatoes, and barley.

Many studies have assessed the net energy return to ethanol production from corn production, considering the energy from N fertilizer production. Shapouri et al.<sup>40</sup> reported positive energy values for just 6 of 10 studies that assessed the energy efficiency of producing ethanol from corn grain. However, in several studies, positive energy yield was only possible by considering co-products such as gluten meal, gluten feed, and corn oil.<sup>37,41,42</sup> These studies did not address the impact of N fertilizer on ethanol and energy yields.<sup>7,39</sup> The purpose of this chapter is to use five case studies to demonstrate how GIS-based SSNM approaches can be used to improve energy costs and efficiencies.

## 21.3 CASE STUDY 1: N IMPACTS ON ENERGY PRODUCED IN COTTON

### 21.3.1 METHODS

The description and results of this 3-year study were published in Bronson et al.<sup>24</sup>. The study site is near Lamesa, Texas, approximately 100 km south of Lubbock, Texas and consists of 14 ha under a 48 ha center-pivot irrigation system. The soil at this site is an Amarillo fine sandy loam (fine-loamy, mixed, superactive, thermic, Aridic Paleustalf). The experimental design was a randomized complete block with three replicates.

The experiment consisted of three N treatments (zero-N, blanket-rate N, and variable-rate N). The N management plots were eight rows wide, and since the rows were planted in a circular fashion, plot lengths ranged from 500 to 1000 m (Figure 21.3). In March of each year, soil samples were taken at differential global positioning system (DGPS)-referenced points within the 14 ha experimental area on a 0.2 ha grid. Two subsamples were taken of the 15–30, 30–60, and 60–90 cm depths with a Giddings soil sampling machine (Giddings Machine Co., Windsor, Colorado), within 3 m of the DGPS point.

Soils from all depths were analyzed for KCl-extractable  $\text{NO}_3\text{-N}$ .<sup>43</sup> The N fertilizer rate for both the blanket-rate N and variable-rate N treatments was calculated using an N supply requirement of  $134 \text{ kg N ha}^{-1}$  for a constant yield goal of  $1100 \text{ kg lint ha}^{-1}$ ,<sup>44</sup> minus extractable soil  $\text{NO}_3\text{-N}$  in 0–60 cm soil. Nitrogen was applied as urea ammonium nitrate (UAN) ( $320 \text{ g N kg}^{-1}$ ) with a liquid fertilizer system fitted with spoke applicators. Half of the N fertilizer was applied at 3 weeks after planting and half was applied at 5–6 weeks after planting (early fruit set or squaring). The blanket rate of N fertilizer was based on the average 0–60 cm soil  $\text{NO}_3\text{-N}$  content of the nine blanket-N plots. Inverse distance interpolation of 0–60 cm



**FIGURE 21.3** Blanket-rate, variable-rate, and zero-N fertilizer strip plots in center-pivot cotton of case study 1, Lamesa, Texas, 2002.

$\text{NO}_3\text{-N}$  values from all DGPS points was used to create variable-rate application maps in 2002.

In May of each year, Roundup Ready® cotton was planted into glyphosate-(isoprophylamine salt of N-phosphonomethyl glycine) terminated rye in 1 m rows at a seeding rate of  $18 \text{ kg ha}^{-1}$ . Hand harvesting of lint and seed were done on 8 m of row at each DGPS-referenced point in October of each year. The hand samples were ginned on a one-saw plot gin equipped with a one-stage lint cleaner to give a unique percentage turnout of lint for each DGPS point.

Energy from N fertilizer was calculated by multiplying the N rate by  $65 \text{ MJ kg}^{-1}$  (Table 21.1). Gross beef cattle maintenance (GBCM) energy was calculated by first calculating total digestible nutrients (TDN) and then metabolizable energy with the following equations:

$$\text{TDN} = 40.26 + (0.1969 * \text{CP}) + (0.422 * \text{NFE}) \\ + (1.19 * \text{Fat}) - (0.1379 * \text{CF}).^{45}$$

$$\text{ME (MJ kg}^{-1}\text{)} = 0.1516 * \text{TDN}^{45}$$

$$\text{GBCM} = -0.508 + (1.37 * \text{ME}) - 0.3042 * \text{ME} * \text{ME} \\ + (0.051 * \text{ME} * \text{ME} * \text{ME}).^{45}$$

$$\text{Net energy}_{\text{fertilizer}} = \text{gross energy} - \text{N fertilizer energy (Table 21.2)}.$$

where

CP is crude protein (%)

NFE is nitrogen-free extract (%)

Fat is in %

CF is crude fiber (%)

ME is metabolized energy

TDN is total digestible nutrients

Net energy<sub>fertilizer</sub> is the net return of cottonseed energy to N fertilizer application

### 21.3.2 RESULTS

Cotton lint and seed yields responded to N fertilizer in all 3 years of the study.<sup>24</sup> The delta yields of the SSNM treatment improved each year, such that by the third season, yields with variable-rate N were significantly greater than the blanket-N treatment. Averaged across the 3 years, N fertilizer responses in cottonseed yield and protein above the zero-N treatment were observed (Table 21.2). There was no difference between blanket-rate and variable-rate N in seed yield, protein, or fat. Nitrogen fertilizer rates were similar between the two N-fertilized treatments in all 3 years of the study. Fat yield averaged  $383 \text{ kg ha}^{-1}$  and was not affected by N. Multiplying fat yields by  $45.2 \text{ MJ kg}^{-1}$  (higher heating value of cottonseed methyl

**TABLE 21.2**

**CottonSeed, Protein, Fat, and Energy Yields as Affected by Variable-Rate N Fertilizer Management with Center-Pivot Irrigation, Lamesa, Texas, 2002–2004**

<b>Nitrogen Treatment</b>	<b>Nitrogen Applied (kg ha<sup>-1</sup>)</b>	<b>Fat (kg ha<sup>-1</sup>)</b>	<b>Protein (kg ha<sup>-1</sup>)</b>	<b>Crude Fiber (kg ha<sup>-1</sup>)</b>	<b>NFE (kg ha<sup>-1</sup>)</b>	<b>Seed Yield (kg ha<sup>-1</sup>)</b>	<b>Energy from N Fertilizer Production (MJ ha<sup>-1</sup>)</b>	<b>Gross Energy (MJ ha<sup>-1</sup>)</b>	<b>Net Energy (MJ ha<sup>-1</sup>)</b>
Blanket	89a	386a	386a	395a	523a	1,757a	6,118a	23,380a	17,263b
Variable	85a	383a	389a	387ab	516ab	1,744a	5,838a	23,210ab	17,371b
Zero	0b	380a	307b	361b	487b	1,599b	0b	21,921b	21,921a
LSD	34	42	51	32	36	108	2,060	1,399	1,341

Numbers in a column followed with the same letter are not significantly different from each other ( $p = 0.05$ ).

esters produced with 97% yield,<sup>46)</sup> gives energy from cottonseed oil of 17,311 MJ ha<sup>-1</sup>, averaged across N rates. This value reflects energy from potential biodiesel yields and is 75% of the total energy value, which includes fat energy and feed value of the meal. Gross energy from cottonseed was significantly greater with blanket-rate N than the zero-N. However, when the energy from N fertilizer production was subtracted to give net energy yields, the two N-fertilized treatments resulted in 21% less energy than the nonfertilized plots (Table 21.2). This result is very different from the large net energy returns to N fertilizer in the Missouri corn case studies. The main reason for this negative return to N fertilizer in Texas cotton is that the “delta yield” or cottonseed response to N was only 10% or about 151 kg ha<sup>-1</sup>. However, profitable lint returns to N fertilizer of \$15–25 ha<sup>-1</sup> were observed in 2003 and in 2004.<sup>24</sup>

## 21.4 CASE STUDY 2: SSNM BASED ON NO<sub>3</sub>-N OR CROP REFLECTANCE

### 21.4.1 METHODS

This study was conducted near Lubbock, Texas, on an Acuff sandy clay loam (fine-loamy, mixed, superactive, thermic, Aridic Paleustoll) from 2007 to 2009 and was reported in Nusz.<sup>47</sup> Drip tape was placed in the center of every other furrow at a depth of 12 and water flowed at a rate of 1 L min<sup>-1</sup> at 0.08 MPa. AFD 5065 B2F cotton was planted in mid-May and harvested in late October. The experimental design was a randomized complete block design, one-way factorial with three replications or blocks. Blocks consisted of 40, 1 m rows that were 180 m long. Each block was divided into five, eight-row plots that were randomly assigned to the five N-fertilized treatments. However, for the purposes of this chapter’s emphasis on energy, we only address the zero-N, soil test-based N management, and reflectance-based N management treatments. Each eight-row plot has its own irrigation and fertilizer injection station. The N fertilizer requirement of 134 kg N ha<sup>-1</sup> was based on a 1400 kg lint ha<sup>-1</sup> yield. The requirement was modified based on the amount of nitrate-N contained in the spring soil samples (0–60 cm) and estimated amount of N in the irrigation water (22 kg N ha<sup>-1</sup>). After the credits were subtracted from the requirement, the predicted N rate (71 kg N ha<sup>-1</sup>) was determined (Table 21.3). Nitrogen (UAN) fertilizer was injected into the drip system 5 days a week, between late June (early square) and early August (mid-bloom). In the reflectance-based strategy treatment, the N injection rate was initially set to the 50% of the soil test treatment. Every week, canopy reflectance measurements were made with Crop Circle ACS-210 (Holland Scientific Inc., Lincoln, NE) and GreenSeeker (NTech Industries, Ukiah, CA) spectroradiometers at 1 m above the canopy on one row per plot.

Normalized difference vegetative index (NDVI) was calculated by the equation:

$$\text{NDVI} = \frac{(\text{reflectance}_{\text{NIR}} - \text{reflectance}_{\text{visible}})}{(\text{reflectance}_{\text{NIR}} + \text{reflectance}_{\text{visible}})}$$

**TABLE 21.3**

**CottonSeed and Energy Yields as Affected by Reflectance-Based N Fertilizer Management with Subsurface Drip Irrigation, Lubbock, Texas, 2007–2009**

<b>Nitrogen Treatment</b>	<b>Nitrogen Applied (kg ha<sup>-1</sup>)</b>	<b>Seed Yield (kg ha<sup>-1</sup>)</b>	<b>Energy from N Fertilizer Production (MJ ha<sup>-1</sup>)</b>	<b>Gross Energy (MJ ha<sup>-1</sup>)</b>	<b>Net Energy (MJ ha<sup>-1</sup>)</b>
Soil test based	71	2,676a	4,903	35,603a	30,700b
Reflectance based	49	2,790a	3,388	37,130a	33,742a
Zero	0	2,003b	0	27,452b	27,452c
LSD		158		2,149	2,135

Numbers in a column followed with the same letter are not significantly different from each other ( $p = 0.05$ ).

The remote-sensing-based N rate was calculated by<sup>20</sup>

1. Starting with an N fertilizer injection rate at first square of 50% of soil test-based rate.
2. If  $NDVI_{\text{reflectance-based}}$  was statistically  $< NDVI_{\text{soil test-based}}$ , then the N fertilizer injection rate was increased to match the soil test-based N injection rate.

Hand harvesting of lint and seed were harvested from 8 m of row at three DGPS-referenced points in each 180 m long plot in October of each year. The hand samples were ginned and the unique percentage turnout of lint and seed for each DGPS point was calculated. In the absence of fat and digestible nutrient data, gross energy value of cottonseed was calculated from relationships between seed yield and gross energy in the center-pivot case study for N-fertilized and zero-N plots.

## 21.4.2 RESULTS

Cottonseed yields were much greater in the drip irrigation study (case study 2) than those observed in case study 1 (Table 21.3). Zero-N plot yields were very high with an average total N uptake of 87 kg N ha<sup>-1</sup> (data not shown).<sup>48</sup> Averaged across the 3 years of the study, N fertilizer application resulted in increased seed yields (Table 21.3). Reflectance-based N management and soil test-based management resulted in a 39% and 33% “delta yields,” respectively, above the zero-N seed yield of 2003 kg ha<sup>-1</sup>. When compared with the soil test strategy, the reflectance-based approach recommended 31% less N. This is in contrast to the first case study and suggests greater potential for saving N fertilizer with SSNM of cotton based on canopy reflectance compared to grid soil sampling and variable-rate N maps. The lower N usage and greater seed yields and delta seed yields resulted in a positive energy return to N fertilizer compared to the zero-N treatment. Notably, the site-specific, reflectance-based approach had significantly greater net energy return than the soil test-based N management (Table 21.3).



## 21.5 CASE STUDY 3: VARIABLE-RATE N BASED ON CROP REFLECTANCE

### 21.5.1 METHODS

Reflectance sensors like those described in case study 2 were used to control variable-rate N applications to over 100 corn fields in Missouri. These fields are part of a demonstration program conducted by the University of Missouri. When possible, these demonstrations included multiple (3–15) replicates of two N rate strategies: a constant N rate chosen by the producer and a variable-rate N application controlled in real time by crop reflectance sensors. Both Crop Circle (ACS-210) and GreenSeeker (red light model) sensors were used in these demonstrations. From 2004 to 2008, there were 55 fields with side-by-side comparisons between constant- and variable-rate N management. We will present the story of one of those fields in this case study.

The study field was located in Audrain County, Missouri, in 2007. All practices were carried out by the cooperating producer. Corn was planted on 24 April at a rate of 75,000 seeds ha<sup>-1</sup>. A high-N reference area measuring 10 m × 18 m was installed on 10 May by hand-spreading ammonium nitrate at a rate of 240 kg N ha<sup>-1</sup>. No pre-plant or early-season N fertilizer was applied to the rest of the field. Irrigation was applied through a center-pivot system as needed.

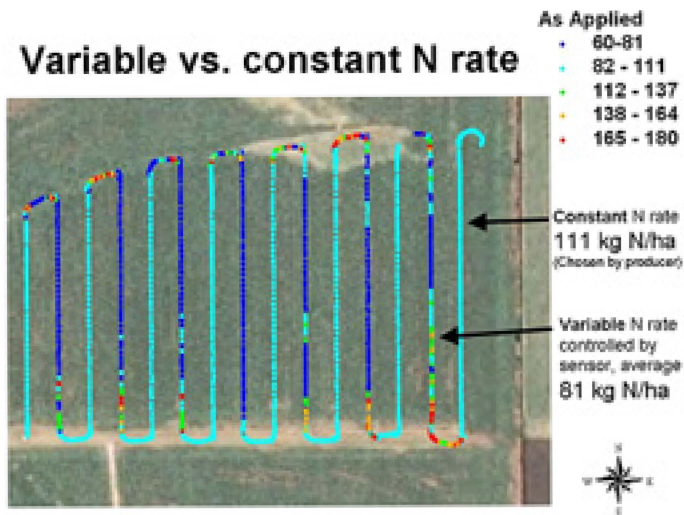
Constant and variable-rate treatments were applied on 13 June, when corn was at the V8 growth stage (about thigh high). A Rogator sprayer equipped with drop nozzles and a 25 m boom was used to apply UAN solution between corn rows. Two GreenSeeker sensors were mounted on a custom-made boom on the front of the Rogator. Custom software averaged the values from the two sensors each second (about 10 values per sensor per second) and converted this average to an N rate using an equation similar to those published by Scharf and Lory<sup>28</sup> and Schmidt et al.<sup>29</sup> This equation requires a value measured from the high-N reference area; therefore, we measured the red/near-infrared ratio of the high-N reference area first, and then used this value in calculating N rates in the variable-rate demonstration areas using the equation:

$$\text{N rate (kg N ha}^{-1}\text{)} = 280 \times \frac{\text{red}_{\text{sample}}/\text{NIR}_{\text{sample}}}{\text{red}_{\text{reference}}/\text{NIR}_{\text{reference}}} - 224$$

where

the  $\text{red}_{\text{sample}}$  and  $\text{NIR}_{\text{sample}}$  were the reflectance values at the demonstration site  
 $\text{red}_{\text{reference}}$  and  $\text{NIR}_{\text{reference}}$  were the reflectance values in the well-fertilized controls

The actual rates of N fertilizer applied to the fields were developed after discussions with the collaborating producer. After this discussion, the minimum and maximum rates of 60 and 180 kg N ha<sup>-1</sup> for the sensor-based N treatment were selected. In the constant N rate strip, 112 kg N ha<sup>-1</sup> was applied. Nitrogen rates applied to this field are shown in Figure 21.4. The average N rate based on sensor measurements was 30 kg N ha<sup>-1</sup> lower than the rate chosen by the producer.



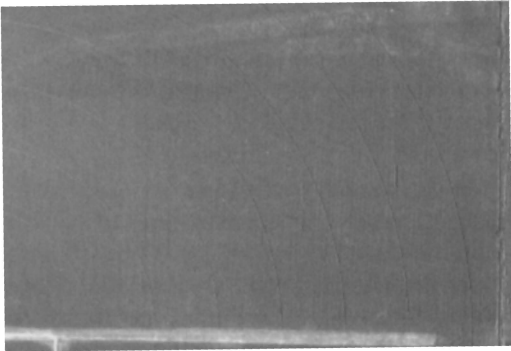
**FIGURE 21.4** Nitrogen fertilizer rates applied at corn growth stage V8 in case study 3. Light grey strips are the constant N rate chosen by the producer. Strips with various shades are based on crop reflectance measured by sensors mounted on the front of the N applicator. Use of sensors in this field reduced N use by  $30\text{ kg N ha}^{-1}$ . The photo on which the application data are overlaid is a stock USDA photo (NAIP) and not from the year of the case study.

### 21.5.2 RESULTS

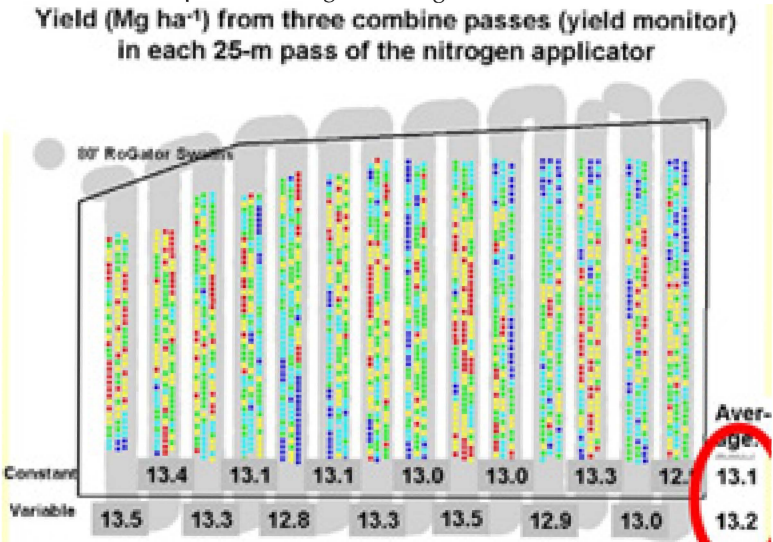
The lower N rates applied with sensor-based SSNM did not result in any apparent deficiency in an aerial photograph acquired 7 weeks after N application (Figure 21.5), nor was yield negatively affected (Figure 21.6).

Notably, the energy balance of this field was improved by using crop sensors to guide N rates (Table 21.4). This field was chosen because it best represents the

August 1 aerial photo:  
7 weeks after the 13 June N application



**FIGURE 21.5** No evidence of N stress is seen in this August 1, 2007 aerial photo of the case study area, providing evidence that the lower N rates recommended by the sensors were adequate to fully supply crop needs for N.



**FIGURE 21.6** Yields were high in both treatments. Nitrogen rates supplied by the sensor-based variable-rate N treatment were sufficient to produce yields as high as, or higher than, the N rate chosen by the producer while reducing total N use by 30kg N ha<sup>-1</sup>.

**TABLE 21.4**  
**Energy Outcome for Spatially Variable N Application**  
**Based on Reflectance Sensors in Case Study 3**

Nitrogen Strategy	Value for Parameter			
	Grain Yield (Mg ha <sup>-1</sup> )	Feed Energy (GJ ha <sup>-1</sup> )	N Rate (kg ha <sup>-1</sup> )	N Production Energy (GJ ha <sup>-1</sup> )
Constant	13.1	214	111	-7.3
Sensor (variable)	13.2	215	81	-5.3
Difference	0.1	1	-30	2

Energy for the production of N is shown as negative to indicate consumption of energy. Sensor-based variable-rate N saved 2 GJ ha<sup>-1</sup> of energy that would have been used to produce the additional N used in the producer’s normal N rate while maintaining or increasing the feed energy output in the corn grain produced.

average energy outcome of the 55 fields for which we have replicated comparisons of a constant N rate (chosen by the producer) with variable N rates (guided by sensor measurements in real time) (Table 21.5). Thus, in our experience, an outcome of using sensor technology to guide N rates is to improve the energy balance of the system. It is apparent in Tables 21.4 and 21.5 that feed energy values used for corn grain result in system energy outputs that far outweigh energy inputs as N fertilizer. However, this energy output is in a very different form than the hydrocarbon energy input (as methane) used in N fertilizer production. Comparing hydrocarbon energy inputs to hydrocarbon energy outputs (as ethanol fuel) is in many ways a

**TABLE 21.5**  
**Average Energy Outcome for 55 Fields with Demonstrations**  
**of Spatially Variable N Application Based on Reflectance Sensors**  
**(Similar to Case Study 3)**

Nitrogen Strategy	Value for Parameter			
	Yield (Mg ha <sup>-1</sup> )	Feed Energy (GJ ha <sup>-1</sup> )	N Rate (kg ha <sup>-1</sup> )	N Production Energy (GJ ha <sup>-1</sup> )
Constant	9.8	160	130	-9
Sensor (variable)	9.9	162	116	-8
Difference	0.1	2	-14	1

Energy for the production of N is shown as negative to indicate consumption of energy. Sensor-based variable-rate N saved 1 GJ ha<sup>-1</sup> of energy that would have been used to produce the additional N used in the producer's normal N rate while increasing the feed energy output in the corn grain produced by 2 GJ ha<sup>-1</sup>. Net energy gain to sensor-based N management is 3 GJ ha<sup>-1</sup>; this value is the same as for the field in case study 3, which was chosen because it best represented the energy outcome from the entire group of demonstration fields.

more appropriate analysis. Using average values cited by references from Shapouri et al.,<sup>40</sup> for energy inputs and outputs in ethanol production from corn grain, we calculated that in-season application of a constant N rate in our 55 demonstration fields increased net energy output by 13% (relative to state-average values representing mainly preplant N application) (Figure 21.7).

Variable-rate N fertilization based on crop sensors increased net energy output by 29%, again relative to state average values for yield and N rate. This shows the importance of efficient N management to the energy balance of ethanol, and the potential for spatially variable N management to increase N efficiency and energy output.

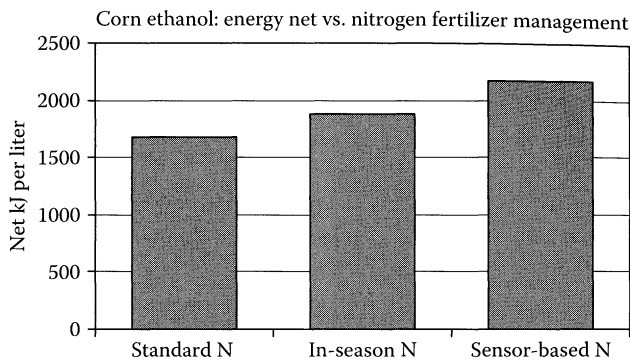
**21.5.3 Use of GIS**

Although GIS is not, strictly speaking, required to implement this SSNM approach, it was needed to help communicate the results with the producers and provide an opportunity for the producers to override treatments (Figure 21.4). A secondary benefit of the technology was that it could be used as a training tool where the producers could compare their knowledge with the predications (Figure 21.6).

**21.6 CASE STUDY 4: CORN REFLECTANCE AND MANAGEMENT ZONES**

**21.6.1 BACKGROUND**

The amount of N needed by crops varies within fields<sup>11,12</sup> and is most often attributed to soil and landscape properties that affect soil N supply (i.e., mineralization) and



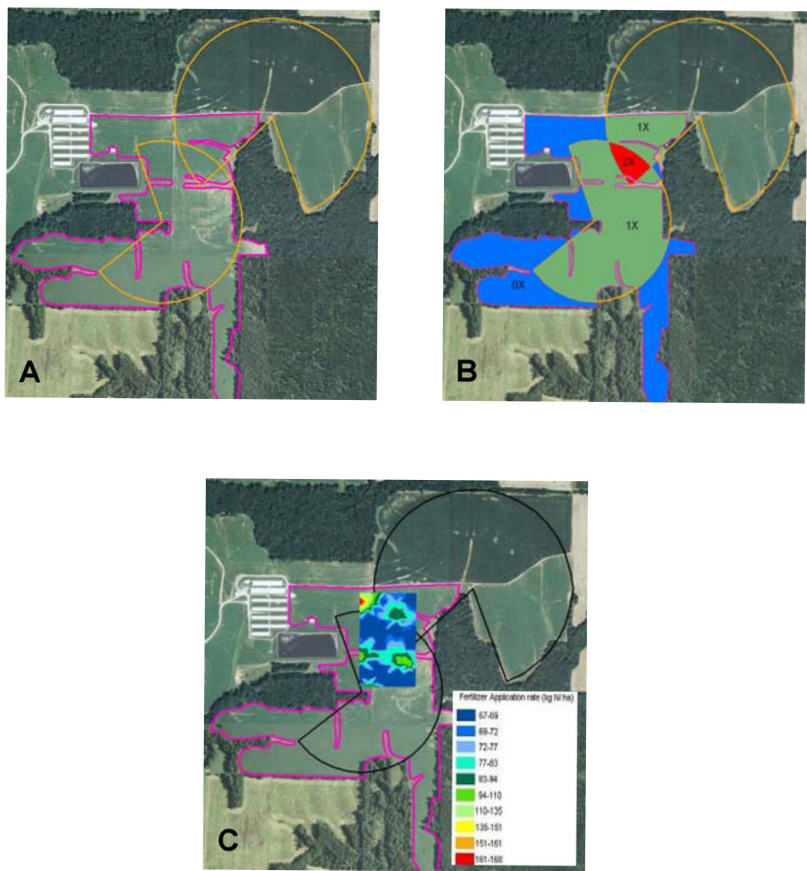
**FIGURE 21.7** Net energy gain to corn ethanol production as a function of N fertilizer management strategy. Net energy gain for standard N management is taken as the average of 10 (widely varying) estimates presented in Table 1 of Shapouri et al.<sup>40</sup>. Nitrogen use per unit of corn grain for standard N management was taken from Table 3 of Shapouri et al.,<sup>40</sup> then converted to energy required to produce the N to grow the corn to produce a liter of ethanol. Average nitrogen use and corn grain yield for 55 demonstration fields in Missouri were used to calculate N energy savings per liter ethanol for in-season and sensor-based N management. These calculated savings were added to the net energy estimate for standard N management. “In-season N” is the constant N rate chosen by the producer in our sensor N demonstration fields. Improved N management, and specifically N management that accounts for spatially variable N needs, can substantially improve net energy gains in corn ethanol production.

soil water supply.<sup>19,48</sup> However, the variability in nutrients need can be further exacerbated by historic and current management practices.<sup>49</sup> The following swine (*Sus scrofa* L.) manure management case study demonstrates how management zones and in-season crop reflectance can be integrated. In this case study, management zone maps were created to represent three unique levels of slurry manure application. These maps were then used in concert with in-season corn canopy reflectance sensing to target SSNM. The goal of this field-scale project was to determine if N fertilizer inputs could be reduced and optimal yields maintained when using this variable-rate strategy as compared to a uniform N application.

21.6.2 METHODS

A 49 ha Missouri field located near a large swine production facility is uniquely managed during the growing season with lagoon effluent applications through center-pivot irrigation systems. Figure 21.8A provides an aerial view of the operation with two overlapping center-pivot systems.

The boundary of the case study field is shown in white on this same figure. Soil mapping indicates five unique soils (primarily Vertic Epiaqualfs and Vertic Albaqualfs), with topography varying from 0% to 9% slope. The field sits in the landscape adjacent to continuous deciduous forest, which blocks the center-pivots from completing a full 360° circle (Figure 21.8A).



**FIGURE 21.8** A case study is provided showing how GIS tools were used on a Missouri corn field to integrate manure management zones with reflectance sensing to do variable-rate N applications. Panel A shows the case study field boundary (white line) along with coverage of two partial center-pivot systems. Panel B shows the slurry management zones of the case study field, with some field area receiving no-slurry (0X, dark grey), some areas receiving slurry from one center-pivot (1X, white), and some receiving slurry from both center-pivots (2X, medium grey). Panel C provides the 2006 variable-rate N map that was obtained on a portion of the case study field using the management zones (panel B) and canopy reflectance sensors.

Swine lagoon effluent is applied through the center-pivots twice during the growing season. The primary purpose of the center-pivots is not for water irrigation, but to apply the effluent to cropland. The first manure application occurs during early corn vegetative growth stages (V3–V5). The second typically is planned during the mid-to late-season vegetative growth stages (V12–V16). Historic nutrient content testing and monitored slurry rates have shown that an average of 45 kg of inorganic N ha<sup>-1</sup>

was applied with each center-pivot application. Thus as shown in Figure 21.8B, some areas of the field receive no manure (in dark grey as 0X), some receive slurry from either one of the two center-pivots (in white as 1X), and a small portion of the field receives slurry from both center-pivots (in medium grey as 2X). Respectively, these three areas receive through manure applications approximately 0, 90, and 180 kg N ha<sup>-1</sup> during the growing season.

Additional N fertilization as fluid UAN was sidedressed between V8 and V10. The applicator was equipped with crop-canopy reflectance sensing and a variable-rate controller that with each pass traversed thirty-two 0.76 m spaced corn rows. Details for sensor mounting and operating procedures are similar to that described previously.<sup>30</sup> The timing of this in-season N fertilization was between the two center-pivot lagoon effluent applications. It was presumed the crop had taken up N from the first slurry application, and that crop canopy sensing would detect differences as the boundary between no-slurry and slurry was crossed. Since the second slurry application was planned after the canopy-sensed N fertilization, a credit of up to 45 kg N ha<sup>-1</sup> (1X areas) or up to 90 kg N ha<sup>-1</sup> (2X areas) was built into the application algorithm, but only for rates called for greater than 67 kg N ha<sup>-1</sup>. This minimum rate of 67 kg N ha<sup>-1</sup> was built into the algorithm to ensure that an adequate amount of N would be available to corn late in the growing season.

A study was conducted on a portion of this case study field in 2006 and 2007. The study area is represented by the rectangle shown in Figure 21.8C. Within this area, uniform (151 kg N ha<sup>-1</sup>) and canopy-based variable-rate N applications were compared. Treatments were applied in randomized paired strips, oriented north to south, within this area. Within the paired N strips, N rates (recorded from as-applied maps) and grain yield (obtained from combine yield-monitoring maps) were extracted using GIS tools. Based on this information, N response relationships were determined. Nitrogen applications and yield response determined from this study area were presumed representative for the whole field and were used to calculate field-level mass and energy differences between uniform and variable-rate N management systems.

Generalized GIS steps for this analysis using ArcGIS software included (1) the addition of field boundaries, N treatment strips, yield strips, and slurry zones as shape files over the raster aerial image of the case study field; (2) the use of GIS-based tools to calculate the size of the treatment areas; (3) the extraction of yields for the different N treatment strips using the tool “Spatial Analyst/Extraction/Extract by Mask”; and (4) the use of an Excel spreadsheet to calculate N responses and energy efficiency (Table 21.6).

### 21.6.3 RESULTS

Using the strips of sensor-based variable-rate N from 2006, a variable-rate map was generated using ordinary kriging interpolation methods, and this is shown overlaid on the field aerial photo in Figure 21.8C. The most notable feature is the relative increase in N fertilizer rate in the northwest corner, where slurry was not applied. Much of the test area under center-pivot only received 67–83 kg N ha<sup>-1</sup>, regardless of whether it was in the 1X or 2X slurry zones. Based on the experimental protocol, a minimum of 67 kg N ha<sup>-1</sup> was applied to all areas.



**TABLE 21.6**  
**Nitrogen Application Rates and Corn Yield Response Are Shown in Energy Metrics for Both Uniform and Variable-Rate N Management Systems on a 49 ha Missouri Corn Field over 2 Years**

	No-Slurry Zone		1× Slurry Zone		2× Slurry Zone		Area-Weighted Average or Total		Field-Level Difference
	Uniform	Variable	Uniform	Variable	Uniform	Variable	Uniform	Variable	(Uniform—Variable)
Fraction of field	0.46	0.46	0.51	0.51	0.03	0.03			
Area of field (ha)	22.36	22.36	24.77	24.77	1.49	1.49			
<b>2006</b>									
<b>Nitrogen fertilizer</b>									
Average rate									
Mass (kg N ha <sup>-1</sup> )	151	136	151	72	151	68	151	101	50
Energy (GJ ha <sup>-1</sup> )	9.8	8.8	9.8	4.7	9.8	4.4	9.8	6.6	3.2
Field N usage									
Mass (kg)	3376	3041	3740	1783	225	101	7342	4926	2416
Energy (GJ)	219	198	243	116	15	7	477	320	157
<b>Crop</b>									
Average yield									
Mass (Mg ha <sup>-1</sup> )	9.07	8.89	9.13	9.43	9.46	9.67	9	9	0
Energy (GJ ha <sup>-1</sup> )	148	145	149	154	154	158	149	150	-1.2



Field yield									
Mass (Mg)	203	199	226	234	14	14	443	447	-4
Energy (GJ)	3306	3240	3686	3807	230	235	7222	7282	-61
<b>Net energy (GJ)</b>	<b>3086</b>	<b>3042</b>	<b>3443</b>	<b>3691</b>	<b>215</b>	<b>228</b>	<b>6745</b>	<b>6962</b>	<b>-218</b>

**2007****Nitrogen fertilizer**

Average rate									
Mass (kg N ha <sup>-1</sup> )	151	140	151	71	151	78	151	103	48
Energy (GJ ha <sup>-1</sup> )	9.8	9.1	9.8	4.6	9.8	5.1	9.8	6.7	3.1
Field N usage									
Mass (kg)	3376	3130	3740	1759	225	116	7342	5005	2336
Energy (GJ)	219	203	243	114	15	8	477	325	152

**Crop**

Average yield									
Mass (Mg ha <sup>-1</sup> )	5.75	6.36	7.36	7.60	7.68	8.08	7	7	0
Energy (GJ ha <sup>-1</sup> )	94	104	120	124	125	132	109	116	-6.6
Field yield									
Mass (Mg)	129	142	182	188	11	12	322	343	-20
Energy (GJ)	2096	2318	2972	3069	187	196	5254	5583	-329
<b>Net energy (GJ)</b>	<b>1876</b>	<b>2115</b>	<b>2728</b>	<b>2954</b>	<b>172</b>	<b>189</b>	<b>4777</b>	<b>5257</b>	<b>-481</b>

Portions of the field received different amounts of swine slurry through a center-pivot irrigation system (see Figure 21.8) and are the basis of the slurry zones shown here. Conversion values used: 65 MJ kg<sup>-1</sup> N; 16.3 GJ Mg<sup>-1</sup> grain.

The N fertilizer applied and grain harvested of the two N management systems were compared on both a mass and energy basis for the whole field (Table 21.6). The N amounts shown do not account for N in the slurry, but only account for differences in N fertilizer. While there was a slight reduction in N fertilizer used in the no-slurry zone using the variable system, the greatest reduction in N fertilizer came in the zones receiving slurry. For these zones, an average of  $79\text{ kg ha}^{-1}$  less N was used with the SSNM system. Significantly, yield was equal or slightly higher with the variable-rate system. While these differences were not statistically tested, the trend observed in both the years was real for this field. When the estimated amount of N that was applied with slurry is combined with the fertilizer N, the total N input for the uniform N system was 241 and  $331\text{ kg N ha}^{-1}$  for the 1X and 2X zones, respectively. Typical corn N rates in this region would not exceed  $200\text{ kg N ha}^{-1}$ . We suspect the slightly lower yields with the uniform system may have been the result of enhanced early-season vegetative growth from excess N, resulting in accelerated soil–water use early in the growing season, and subsequent greater water stress during grain set and grain fill late in the season.

The combination of less N fertilizer used and greater harvested yield with the variable-rate N system produced an average energy benefit over the uniform system of  $7.1\text{ GJ ha}^{-1}\text{ year}^{-1}$ . For this 49 ha field, that translated into an average of  $350\text{ GJ year}^{-1}$  energy savings using the variable-rate system. In hindsight, the variable-rate algorithm probably should have been adjusted so that N credit from the second slurry would have been increased. Had this adjustment been made, without a loss in yield potential, an additional benefit of  $1.8\text{ GJ ha}^{-1}$  or  $79\text{ GJ year}^{-1}$  for the field would have been realized.

In this case study targeting N fertilization to account for both known management differences (by slurry manure zones), as well as less-quantified soil/landscape differences (by canopy sensing), proved to be an effective strategy for decreasing energy inputs and increasing crop energy produced. Such site-specific management and assessment would be impossible without GIS mapping and tools.

## 21.7 CASE STUDY 5: CORN N RATES BASED ON AERIAL PHOTO

### 21.7.1 BACKGROUND

Case studies 2–4 utilize crop reflectance sensors to diagnose N status of corn or cotton, based on the principle that as N need increases, reflectance of visible light increases (and reflectance of near-infrared light often decreases). The same principle can be used to translate information from aerial photographs into N rate decisions.<sup>50,51</sup> The limitation with aerial photographs is that they need to be either acquired after full-canopy development,<sup>51</sup> or acquired at ultra-high resolution so that soil background can be filtered out.<sup>50</sup> Both of these options present substantial logistical difficulties in corn, especially with N application after full canopy, when the corn is tall.

However, in fields with center-pivot irrigation and fertilizer injection pumps, applying N fertilizer after full-canopy development is not a limitation. This situation presents an ideal opportunity to use aerial photographs to guide N rate decisions. We have worked with a small number of producers to try this approach. Our first trial field is presented here.

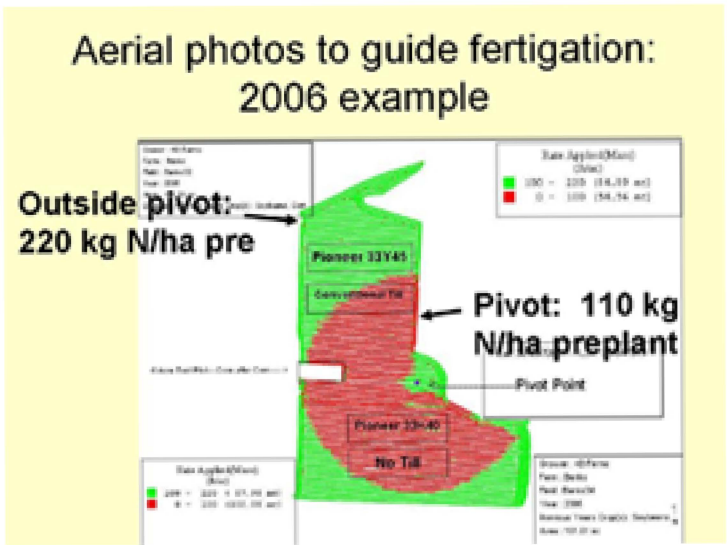
21.7.2 METHODS

Using an approach for photograph interpretation similar to Scharf and Lory,<sup>50</sup> but based on unpublished full-canopy (growth stages V10–V16) aerial photographs, green values were translated into N rate recommendations. Details for this calculation are provided below.

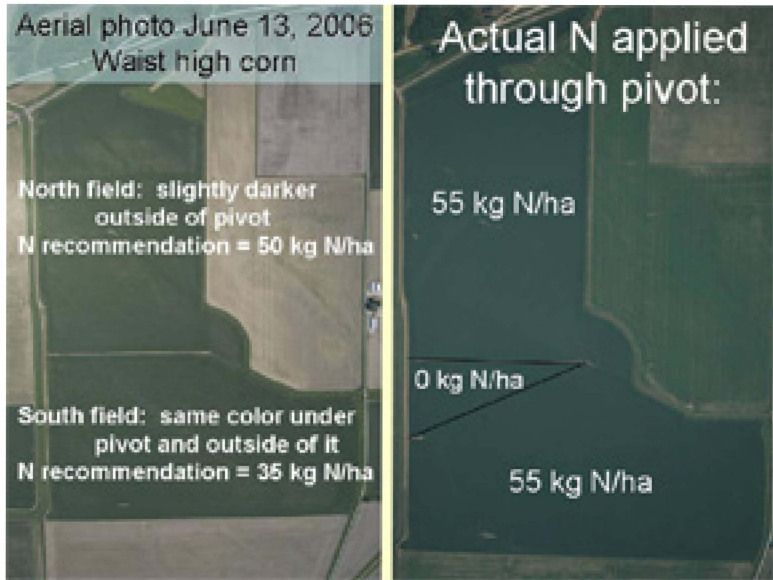
This approach relies on having a high-N reference area to compensate for the effects of growth stage, hybrid, and photographic procedures on the measured greenness of the corn. The producer created a field map with the area under the center-pivot defined as a separate zone in the field. He then applied anhydrous ammonia at his normal rate ( $220 \text{ kg N ha}^{-1}$ ) outside of the center-pivot zone, but at half that rate under the center-pivot (shown as dark grey in Figure 21.9), knowing that he could easily supplement N by injecting UAN solution into the center-pivot water.

The area outside of the center-pivot thus acted as the high-N reference area. The areas north and south of the center-pivot point were managed as two separate fields and were planted to different hybrids, so they were analyzed separately, each with its own high-N reference area.

A digital aerial photograph of the study field was acquired on 13 June when the corn was approximately waist high (growth stage V11) (Figure 21.10).



**FIGURE 21.9** Preplant N applications to the case study field. Areas outside of the irrigation center-pivot’s reach (light grey) received the producer’s normal N rate of  $220 \text{ kg N ha}^{-1}$ . Areas under the center-pivot received half that rate (dark grey), with the plan to supply additional N in the irrigation water at rates suggested by analysis of an aerial photograph. This analysis requires comparing the area to be fertilized with a high-N reference area of the same hybrid. The areas north and south of the center-pivot point were planted to different hybrids, so they were analyzed independently, with the light grey area outside of the center-pivot’s reach serving as the high-N reference area for each half of the field.



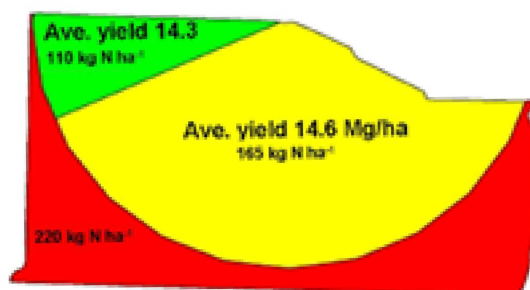
**FIGURE 21.10** An aerial photo acquired on June 13, 2006 showed little evidence of N stress in the areas of the field that had received half of the producer’s normal N rate. Image analysis gave relative green values of 1.0 in the south field and 1.05 in the north field, translating into N rate recommendations of 35 and 50 kg N ha<sup>-1</sup>, respectively. A relative green value of 1.0 means that average green value is the same for the high-N and low-N areas, and they are indistinguishable from each other. Our calibration data suggested that even when a low-N area shows no visible N stress at this stage, it may sometimes need N. For simplicity’s sake, the producer applied 55 kg N ha<sup>-1</sup> over the entire field with his first irrigation, except in a small wedge of the south field where he applied no N in the irrigation water to allow us to estimate yield response.

No irrigation water had been applied. The photograph was georeferenced, field zone boundaries overlaid (under the center-pivot vs. outside the center-pivot), and average green value was measured for seven areas: north high-N zone, two north low-N zones (dark grey in Figure 21.9, divided radially), south high-N zone, and three south low-N zones (again divided radially). Relative green value was calculated for each of the five low-N zones by dividing their average green value by the average green value of the corresponding high-N zone.

### 21.7.3 RESULTS

Average green value was nearly identical for all four south zones, giving relative green values of 1.0 for all of the south low-N zones. Our calibration data suggested that even when the low- and high-N zones have similar colors, an additional 35 kg N ha<sup>-1</sup> is needed to optimum profits in the low-N areas. In the north half of the field, N stress was also not immediately apparent in the area receiving the low-N rate (Figure 21.10). However, image analysis revealed that the high-N

### South field: N rates and yields



**FIGURE 21.11** Yield outcome of reduced (light grey) vs. zero supplemental N in irrigation (medium grey) N rates for this case study. The very small difference in yield shows that the  $165 \text{ kg N ha}^{-1}$  N rate was at or above the economically optimal N rate for this field, and that no economic penalty resulted from reducing N rates relative to the producer's normal  $220 \text{ kg N ha}^{-1}$  N rate. This use of imagery/GIS saved 640 GJ of energy that would have been used to produce the N fertilizer that was saved.

area outside the center-pivot was slightly darker green than the two areas under the center-pivot (relative green  $\approx 1.05$ ), resulting in a suggested N rate of  $50 \text{ kg N ha}^{-1}$ . Because the variable N rates were similar for the different zones, the producer opted to apply a constant rate of  $55 \text{ kg N ha}^{-1}$  to the entire field except the zero-N control area. The purpose of the no-N control area was to assess the N responsiveness of the site.

GIS analysis of the south field showed a slightly lower yield in the unfertilized control area than area where  $55 \text{ kg N ha}^{-1}$  was applied (Figure 21.11). However, this yield enhancement was not sufficient to pay for the additional N. This confirms that the optimal N rate for the south field was at or below the rate that it received. By analogy, the same is likely true for the north field. Thus, a substantial amount of N, energy, and money was saved in this field with minimal or no cost in terms of lost yield. For the 64 ha area under the center-pivot irrigation system, calculations suggest that relative to the producer's normal practice of applying  $220 \text{ kg N ha}^{-1}$  to the whole field before planting, SSNM reduced the total N applied by 9910 kg N. This reduced the amount of energy invested in the field by 640 GJ, reduced the production costs by \$3310, and reduced the amount of  $\text{CO}_2$  released into the atmosphere by  $39.2 \text{ Mg CO}_2$ .

## 21.8 CONCLUSIONS

Net energy return to N fertilizer with SSNM can be greater than with conventional, soil-test-based regional, blanket-N applications in cotton and corn. The SSNM approaches tested included grid soil sampling, management zone strategies, aerial photography, and canopy reflectance. Improved energy return to N fertilizer with SSNM was usually due to N savings without a reduction in yield.

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